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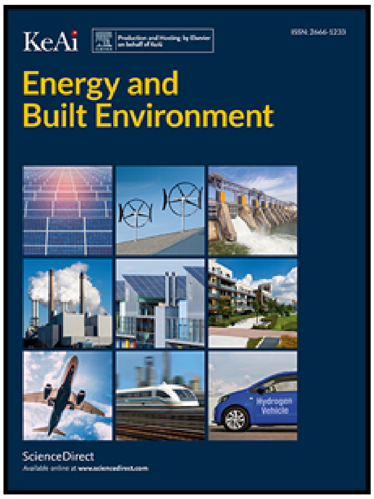

Empirical investigation to explore potential gains from the amalgamation of Phase Changing Materials (PCMs) and wood shavings

Adham M. Mohammed , Amira Elnokaly , Abdel Monteleb M. Aly

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Highlights:

- Panels containing PCM, Wood-shaving and PCM/wood-shavings amalgams are created.
- Panels are subjected to heat profiles and their thermal performances were compared.
- Heat peak reduction, heat peak shift and fluctuation of temperatures are examined.
- Amalgamation of wood-shavings did not improve the PCM's thermal performance.
- The overall weight of the panels was reduced due to amalgamating wood-shavings.

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Empirical investigation to explore potential gains from the amalgamation of Phase Changing Materials (PCMs) and wood shavings

Adham M. Mohammed [a]*, Amira Elnokaly[b] and Abdel Monteleb M. Aly [c]

[a, c] Department of Architecture, University of Assuit, Egypt; [b] School of Art and design, University of Lincoln, UK.

**Corresponding author, email: adham@aun.edu.eg*

Abstract

The reduction of gained heat, heat peak shifting and the mitigation of air temperature fluctuations are some desirable properties that are sought after in any thermal insulation system. It cannot be overstated that these factors, in addition to others, govern the performance of such systems thus their effect on indoor ambient conditions. The effect of such systems extends also to Heating, Ventilation and Air-conditioning (HVAC) systems that are set up to operate optimally in certain conditions. Where literature shows that PCMs and natural materials such as wood-shavings can provide efficient passive insulation for buildings, it is evident that such approaches utilise methods that are of a degree of intricacy which requires specialist knowledge and complex techniques, such as micro-encapsulation for instance. With technical and economic aspects in mind, an amalgam of PCM and wood-shavings has been created for the purpose of being utilised as a feasible thermal insulation. The amalgamation was performed in the simplest of methods, through submerging the wood shavings in PCM. An experimental procedure was devised to test the thermal performance of the amalgam and compare this to the performance of the same un-amalgamated materials. Comparative analysis revealed that no significant thermal gains would be expected from such amalgamation. However, significant reduction in the total weight of the insulation system would be achieved that, in this case, shown to be up to 20.94%. Thus, further reducing possible strains on structural elements due to the application of insulation on buildings. This can be especially beneficial in vernacular architectural approaches where considerably large amounts and thicknesses of insulations are used. In addition, cost reduction could be attained as wood shavings are significantly cheaper compared to the cost of PCMs.

Keywords: PCMs; Heat peak; Heat peak shift; Thermal performance; Wood shavings; By-products.

1. Introduction

To achieve higher comfort levels of occupants, traditional architecture incorporated varied aspects such as natural ventilation, shading, thermal mass and passive cooling techniques as some of the most important passive design features of traditional architecture [1,2]. In hot-arid climate regions, 70-80% of total energy consumption is used to operate active cooling systems [3], and consequently, reducing the reliance on those will have a drastic impact on energy consumption. An optimized envelope design can improve the thermal performance through passive solar techniques [4–7]. Some of the other variables that influence indoor thermal comfort includes: thermos-physical properties of the building’s envelope material [8]; the roof optical properties, namely the albedo, thermal emissivity and building insulation [5,9–11] that play an important role in the energy balance of buildings. Indoor air temperature is one of the important factors that contributes to achieving thermal comfort of occupants inside buildings [12,13] [14–16]. It is evident that the outdoor heat loads that a building is exposed to may affect the indoor air temperatures as heat is conducted through the building’s envelope. Many passive attempts to limit the effect of exterior heat on interior temperatures have been, to a good extent, successful [17–20]. This results in a lowered indoor temperature which increases thermal comfort in hot climates and reduces strain on HVAC systems caused due to heat overload on these devices [13,21–24].

In last couple of years, PCMs have been extensively researched as a possible part of passive thermal control methods. Many researchers have attempted to utilize them in different ways [25–31], which have shown good potential. The innovative manner in which PCMs have been utilised has been miscellaneous. Methods such as using a layer of paraffin wax on brick walls and inside building envelopes which has shown to be successful in reducing indoor air temperatures and related cooling electricity consumption of up to 75% [32–41]. Other studies have attempted utilise "PCM immersion" of building elements such as PCMs infused wallboards [42–45,39], PCM-mortar [46–51], PCM infused bricks [52–54], PCM-concrete [55–66] and PCM-enhanced plaster [67–69]. Such methods have reported the ability to reduce indoor temperatures by up to 5 °C. Similarly, the combination of PCMs and other materials such as Silica, Graphene and Gypsum has also been investigated with promising results as to the thermal performance [70–78]. Also, the incipient field of Nano-technology has allowed for much progress in this regard by adding certain types Nano-particles to enhance PCM mixtures [31,79–83]. In terms of methods of utilising PCMs, encapsulation of PCMs seems to provide a good potential as a passive thermal control technique [84–92]. The encapsulated PCM is used also in various manners. Macro-encapsulated PCMs can be used to fill void in brick walls which show a possible reduction in temperature of up to 6.31°C or 25% of peak temperatures [29,93–95]. Similarly, macro-encapsulated PCMs can be placed in bags which also show a decrease in peak indoor temperatures, reported to be around 12.04 to17.26% [96–98].

Traditional methods have also shown good thermal performance, in many cases comparable to modern passive thermal control methods [99–102]. Such methods involve using copious natural materials such as stone, mud, fabrics, plant segments and wood, utilised in various ways [101]. With the abundance of suitable natural materials, wood shavings have been the focus of investigation as it has shown good thermal behaviour. In addition, wood shavings are commonly found as a by-product in wood workshops and through industrial process. In many cases, it is disposed of with no significant use [103], which consequently results in it being of low cost, thus, further expanding the feasibility of usage. Furthermore, wood shavings are low in density compared to materials such as PCMs, resulting in lower weights. Also, utilization of wood-waste in particular is seen to be of desirable environmental impacts [102,104], which includes many forms such as cork, wood fibre and hemp. It is further explained that the advantageous thermal properties are a result of certain

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characteristics such as lower embodied energy, moisture buffering capacity compared to other inorganic materials [104]. In addition to its low thermal conductivity that ranges from 0.048 to 0.055 W/mK, which is comparable to other commercial insulation materials [102,104–106]. Furthermore, waste wood can be formed into panel-like shape that can act as effective thermal insulation with a density of around 315 kg/m^3 and a thermal conductivity of around 0.08 W/m/K [106,107]. It is worthy to note that many segments of various types of plants are considered to be composed of wood-fibres, especially plants stalks and stems. Under certain conditions, these segments can be utilized to act as actual wood-fibres, which that have been found to provide good thermal behaviour, be cost-effective and have less environmental impact [15,99,103,107–112][103,111,112]. Such plant segments can include cotton-stalk [113–117], date palm branches [118], tomato-stalks [119], sun flower [120], corn cob [121], straw-bale [122–125], bamboo [41]and poppy husk [126]. Such materials have been utilised in various ways, which has shown thermal conductivities ranging between 0.051 and 0.053 W/(m K) [122] and as low as 0.040 W/mK [125,127,128] in some cases, with heat dampening of 93.6% and a heat time lag of 9.12 h [123].Combined wood particles of different sizes, in to boards, are also a viable approach that has shown efficient performance with thermal conductivities of between 0.1078 W/mK and 0.0742 W/mK [129,130]. It is evident from the previously discussed literature that using wood-related materials as a form of natural insulation is advantageous, with thermal performances similar to this of commercial synthetic materials, in addition to having better environmental impacts.

The mentioned earlier refers to successful attempts to utilise both wood-base materials and PCMs. However, most of these attempts were made through mechanisms that require substantial technical effort such as impregnation of PCMs into the micro-structure of fibrous materials, including wood, through the use of vacuum pressure [131–133]. In the present study, wood shavings were amalgamated with PCMs through submerging. This particular method was utilised as it requires little intricacies thus eliminating cost, effort and technical issues. Hence, the novelty of the present study lays in the experimental investigation of the effectiveness of a simplified amalgamation approach as an alternative to common complex PCM utilisation methods that require intricate technologies to conduct, such as these mentioned earlier. Furthermore, the experimental approach carried out in this case differs from similar studies in terms of the purpose of using wood-shaving. Where most studies perceive such material as an encapsulation medium for the PCM particles as a macro encapsulation [134–138], the present study uses wood-shavings as supplement to PCM, with the goal to enhance its thermal performance as thermal insulation. The aim of the mentioned earlier is to explore possible advantageous gains the may be achieved from such simple method, weather gain of a thermal nature or otherwise. To achieve this, the amalgamated mixture is investigated for many features. Aspects such as heat peak reduction is important and heat peak shift are investigated as they describe the potential of a thermal insulator to impede conduction of heat through facades and the influence of the latent heat storage of such materials [40,41,54,66,97,139–142]. Also, the ability to reduce fluctuations in indoor air temperature has been investigated in this article. This is of significance as outdoor air temperature may fluctuate un-uniformly [20,143,144] causing analogous fluctuations in indoor air temperatures [145,146], which can cause thermal discomfort to inhabitants and affect the performance of HVAC systems exposed to this.

2. Thermal performance of PCM panels

As determined, the tested panel is placed between two controlled environments. To apply the required heat variations on one of the sides of the panel, a climatic chamber was used. To control the initial temperature of the other side, a confinement holding the panel was

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created. As the temperature would vary on the side of the panel that is exposed to the chamber, the other side would gradually be thermally influenced by this variation. Through measuring the air temperature on both sides and comparing them, the effect of the PCM/ PCM-wood shavings could be assessed. The same process was repeated for the control panel (panel with 1 sheet of Plexi-glass) and the 1 cm air gap panel (panel with 2 sheets of Plexi-glass). Figure 1 shows a schematic representation describing the position of the tested panel in relation to the controlled environments applied.

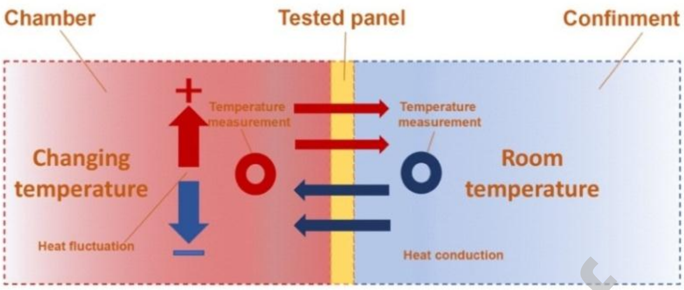

Figure 1: Schematic representation of the experimental procedures carried out on the tested panels (Authors' own).

To choose an appropriate type of PCM for this study several factors were considered. It was considered that the chosen type of PCM is applicable in building applications, thus, having a melting/freezing temperature that is within range of the prevailing temperatures found in some hot climates. It is important to note that literature has pointed out that applications relying on PCMs can fail due to inappropriate melting/solidification temperatures [147]. In addition to being durable and having congruent melting to ensure that it retains original structure throughout numerous cycles of phase change [148,149]. In addition, aspects such as 1) chemical stability; 2) complete reversible freeze/melt cycle; 3) limited degradation; 4) non-toxicity, 5) non-flammability and 6) non-explosiveness and non-corrosiveness where taken in to account [150]. Paraffin waxes are able to provide most of the required criteria described earlier [151]. The PCM initially chosen to be used is Paraffin wax 43/46 obtained from a UK based chemical company (Scientific laboratory supplies SLS) product No. CHE2750, shown in Figure 2 (A&B). Table 1 shows some of physical and chemical properties of the PCM as provided by the supplier.

(A)

(B)

Figure 2: (A) Packaging of Paraffin wax as provided by supplier. (B) Appearance of paraffin wax in the solid phase.

Table 1: physical and chemical properties of the paraffin wax as provided by the supplier.

Appearance	White waxy solid
Odour	Nectareous.
pH	Not applicable
Boiling Point	350°C
Melting Point	43°C
Flash Point	300°C (Closed cup)
Upper Flammable Limit	Not applicable
Lower Flammable Limit	Not applicable
Auto Ignition	Not applicable
Explosive Properties	No.
Oxidising Properties	No.
Vapour Pressure	Not applicable
Relative Density	0.9550
Water Solubility	Insoluble in water.

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2.1. Experimental rig

To conduct the experimental condition described earlier, a rig consisting of several elements was designed. An appropriate container was required to encapsulate the tested material without affecting test results. Factors such as leakage, chemical compatibility and expansion properties of the PCM were taken into account as literature shows that they may be of importance in PCM testing [148,152]. The container used for this experiment was created using sheets of MDF wood that were cut using an Epilog Fusion M2™ Laser cutter and engraver for precise cutting. The container is constructed of a frame of MDF wood with a thickness of 10 mm, with a width of18 mm. The inner dimensions were 20 * 24 cm so as to accommodate the PCM panel (20 * 20 cm) and provide a 20 percent of the PCM volume as void for expansion (4 cm). Four layers of water-sealing varnish coating are applied to ensure that no absorption of the PCM would occur when it is in the liquid phase. The top side of the frame was removable to allow for the materials to be inserted into the container. Both sides of the frame were covered with sheets of Plexi-glass of 2mm thickness using glue. The container after assembly is shown in Figure 3 (A). For comparison purposes, two more panels were created. One of them, a panel that consisted of a single 2 mm layer of Plexi-glass and a wooden frame with the same dimensions as the PCM encapsulation panel, was used as a reference control panel. The other panel was identical to the previously mentioned, however, no materials were placed inside. The purpose of this panel is to test the thermal performance of the two layers of Plexi-glass with an intermediate air gap of 1 cm width.

As mentioned earlier, a five-sided box-like confinement was constructed of isolating materials. The 6th side remained as a void to accommodate the panel under investigation. This allowed the side of the panel that is facing the inner part of the confinement to be exposed (initially) to room temperature while the other side is exposed to the pre-set temperatures. Figure 3 (B) shows the confinement after final assembly, including fibre-wood insulation. The box-like confinement was made of 18 mm thick sheets of medium density fibre wood (MDF) that were cut and assembled with inner dimensions of 20cm*20cm*35cm. To hold the PCM encapsulation panel at the front of the confinement as required, a platform with the same inner dimensions as the panel was created from the same materials. Insulated was made by covering all sides with four layers of wood-fibre sheets (Diall™ Fibre wood underlay) with total thickness of 20mm, shown in Figure 3 (C). An Epilog Fusion M2™ Laser cutter and engraver, shown in Figure 3 (D), was used to ensure accuracy of the cut parts. To subject the PCM panel that are under investigation to environment-like conditions, the panels and the insulated confinement were placed inside an environmental chamber during the testing process. The environmental chamber used was a Panasonic™ versatile environmental test chamber model MLR-352 as shown in Figure 3 (E&F). The chamber has the ability to be programmed to manipulate the temperature of the inner environment to change from 0°C to 60°C. To monitor the change in air temperature of both side of the encapsulation panel throughout the duration of the experiment in which heat was applied, two HOBO® MX Temp/RH Data Loggers model-(MX1101) shown in Figure 3 (G) below are used. The data loggers had built in thermal sensors with a range of -20° to 70°C with an accuracy of ±0.21°C in addition to humidity sensors. The loggers are capable of logging up to one reading per second. Control and setup of the data loggers can be done through an iOS or Android™ device through a Bluetooth® connection. Logged data is also downloaded through the wireless connection mentioned earlier through HOBO mobile® app.

2.2. Experimental procedures

The following depicts details regarding the creation of the three panels in addition to a control panel and an empty panel created for further comparison purposes. A description of the heat profiles applied to the panels with various details is also provided.

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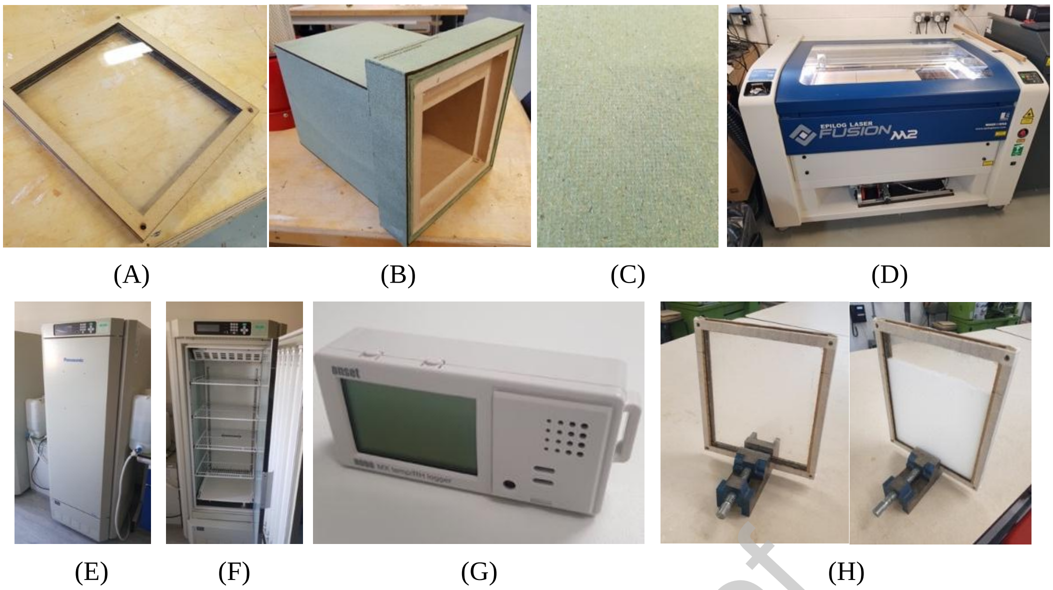

Figure 3: (A) Material container after assembly. (B) The Box-like confinement, with the platform end. (C) Diall™ Fibre wood underlay sheets. (D) Epilog Fusion M2™ Laser cutter and engraver. (E) Exterior of environmental chamber. (F) Interior of chamber, (G) HOBO® MX Temp/RH Data Logger model-(MX1101). (H) Encapsulation panel secured upright using a holder, PCM had been poured in and left to cool, photographed after 10 minutes approximately.

2.2.1. PCM panel testing

To create a PCM panel, 382 grams of the PCM were weighed (the PCM had a density of 0.9550, and the required panel was with dimensions of 20*20*1 cm). This was the amount required to create a panel with the desired dimensions. The PCM was then placed in a steel container then liquefied using an electric hotplate to temperature of 65°C approximately. The liquefied PCM was poured in the encapsulation panel. The encapsulation panel was held upright using a holder shown in in Figure 3 (H) above as the liquefied PCM was poured-in till 200 mm were filled in order to leave 40 mm for expansion as mentioned earlier. The PCM was poured slowly so that to ensure that no air pockets (air-bubbles) had been formed. The panel was left over-night in a relatively cool environment so as to allow for the PCM to solidify. Both the encapsulation and the confinement were then placed inside the environmental chamber, which was then sealed. A series of tests were performed on the panel. In each test, a different heat profile was used. The aim of this is to monitor the performance of the tested materials under different modes of heat loads. It is important to note that two of the heat profiles are used to simulate natural day/night cycles were as the rest was used to simulate different fluctuation in temperatures that may occur in certain environmental conditions. Table 2 depicts the temperatures and durations that the chamber was pre-set to. A difference is identified between the pre-set and actual measured temperatures, due to capabilities. Measurements were set to be logged every 10 seconds.

In heat profile 1, a gradually increasing/decreasing profile was used. The profile was an attempt to simulate the natural gradual increase of temperature that would occur in a hot environment during day time and the decrease of temperature during night. The heat profile ranged from 15°C to 57°C in a duration of 24 hours. Figure 4 (A) shows the temperature inside the chamber during test. In order to achieve a gradually changing temperatures as required, twelve steps of temperatures had to be set. Each step was for the duration of 1 hour and increased in temperature by 7°C. Likewise, Profiles 2-6 were conducted with varying cycles of heat and different durations. Figure 4 (B, C, D, E & F) show the change in temperature according to the setting of each profile.

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Table 2: Pre-set heat profiles

Heat profile	Minimum temp. °C	Maximum temp. °C	Cycles	Cycle duration (hours)	Total duration (hours)
1	15	57	1	24	24
2	15	55	1	12	12
3	35	55	2	6	12
4	35	55	3	4	8
5	35	55	3	2	6
6	35	55	3	1	3

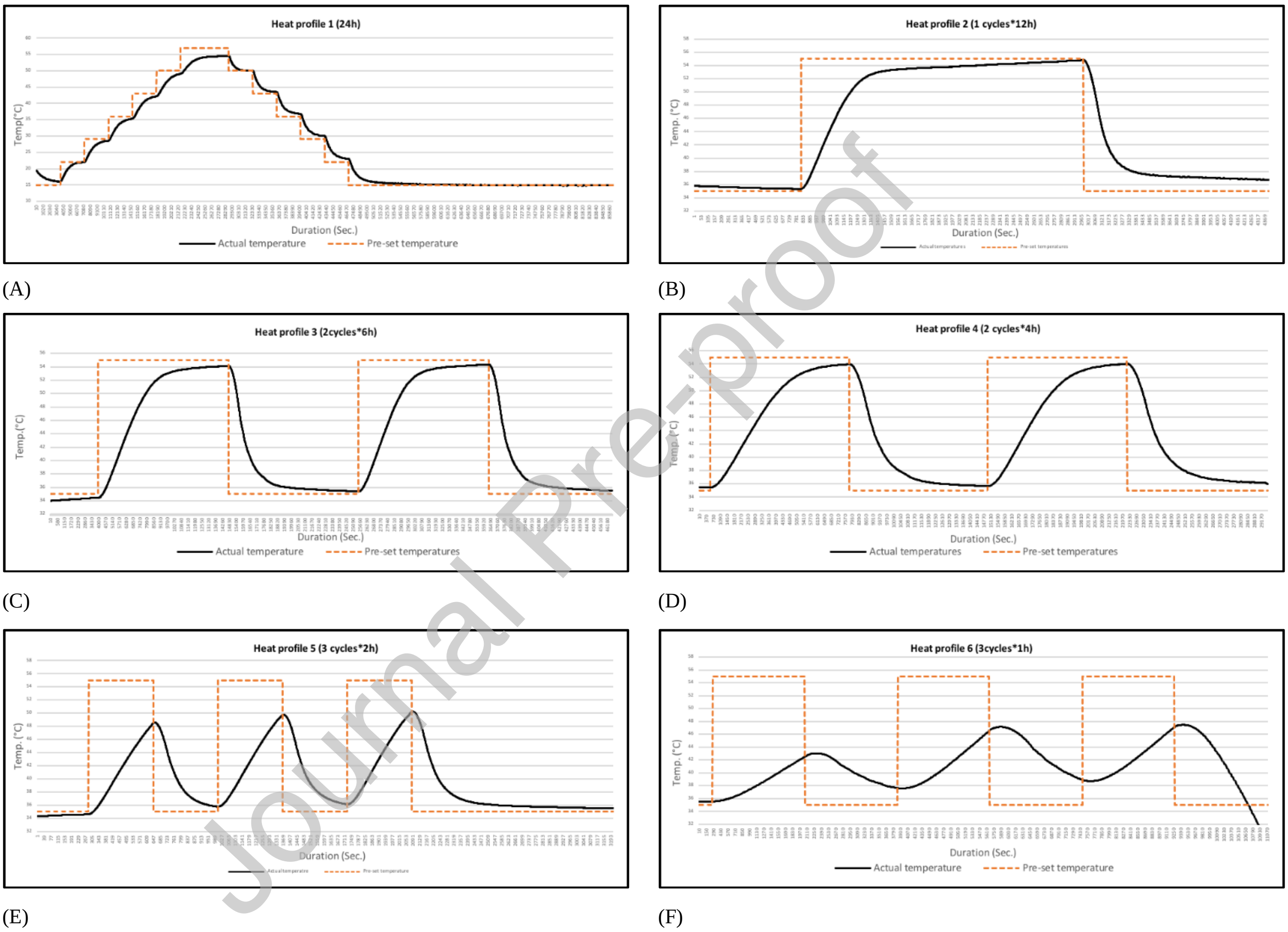

Figure 4: Pre-set and actual temperature inside the environmental chamber for: (A) Heat profile 1, (B) Heat profile 2, (C) Heat profile 3, (D) Heat profile 4, (E) Heat profile 5, (f) Heat profile 6.

2.2.2. Wood shavings filled panel (Ws):

Wood shavings obtained from a local provider were used. The utilized wood shavings were chipping of plywood obtained as a by-product of wood manufacturing processes. The approximate calculated bulk density of the shaving in their loose form was 0.1 g/cm^3. An amount of 40g of wood shavings was placed inside the panel (with dimensions of 20*20*1 cm). This mount was sufficient for the panel to be filled with wood shavings without any form of compression. Figure 5(A) shows the panel filled with the amount of wood shavings.

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2.2.3. PCM/Wood-shavings (PCM/Ws) panel testing

Wood-shavings were obtained from a local provider. To create the mixture of wood-shavings and Paraffin wax, 40g of wood-shavings were weighed on a scale (as 14% of the total weight of the mixture). An amount of 260g of Paraffin wax (86% of the total weight of the mixture) was melted on a magnetic stirrer (set to 60°C) which was used to stir the wood-shavings in the mixture. The wood-shavings were added gradually to the wax while being stirred. This is to ensure that all particles of the wood-shavings have been engulfed with the wax. Once the entire amount of wood-shavings was added to the wax, it was important to manually stir the mixture as it had created a paste-like substance which demanded manual stirring to ensure that the mixture is completely homogenous. It should be noted that the stirring was performed at a constant temperature of 60°C so that to ensure that the wax would remain in a liquefied form throughout the entire process. After being stirred, the mixture left to slightly cool (to around 43°C) to facilitate placing it into the panel for testing. Figure 5(B) shows the slightly cooled mixture. Initial trials have shown that it may be hard to place the mixture in the panel in a liquefied form as it is of high density which makes it difficult to manage placement in a relatively small opening such as this of the panel. Similar to previous tests performed on the PCM panel (described in section 2.2.1), the panel was filled with the created mixture, as shown in Figure 5(C). The panel was cooled to room temperature prior to any testing to ensure that no latent heat would affect testing, which was repeated prior to all tests. Then, the filled panel was placed in its analogues section in the testing confinement which is then placed inside the environmental chamber in the same manner as described earlier in the previously mentioned thermal tests.

(A) (B) (C)

Figure 5: (A) Panel filled with 40g of wood shavings. (B) Mixture of 20% wood-shavings and 80%paraffin wax cooled to a temperature of around 43°C. (C) Panel filled with mixture ready to be placed inside environmental chamber.

2.2.4. Control panel and air gap panel test

As explained earlier, the same tests using the mentioned heat profiles were carried out on the control panel and the air gap panel for comparison purposes.

2.2.5. Verification of measurements

It should be noted that to verify the accuracy of the measurements obtained, several steps were taken. In addition to the measurements mentioned earlier, for profile 2 and profile 6, the measurements were repeated once with the same data logger mentioned earlier and twice with another data logger of the same type. In total, the mentioned tests were carried out four times using two different loggers. These profiles were specifically selected for the verification process as they represent both a short and long-term duration cycle of heat. The results showed that all of the verification tests were in alignment and the deviations in temperature readings were less than (0.05°C) thus suggesting the validity of measurements. In addition to this, all of the profiles were also repeated with an alternate logger (in total two repetitions for each profile). The results of this also showed an alignment with a deviation in measurements less than (0.03°C). Hence, it can be verified that measurements are accurate.

2.3. Results and Analysis

Table 3 shows the results for all the tested panels under the influence of various heat profiles. In the mentioned table, a comparison is presented between results of the panel created with a single sheet of Plexi-glass which simulates a single-panel window referred to as the control panel in this study. Results for the panel consisting of two panels of plexiglass is referred to as the "1 cm" air gap panel, the PCM filled panel is referred to as "PCM panel" and the panel filled with the PCM/wood-shavings mixture is referred to as "PCM/Ws panel". In Table 3, the column named "Chamber temperature ranges" presents the actual temperatures measured inside the chamber during each heat profile. Also, for each panel, the table presents the actual measured temperature ranges (maximum and minimum temperatures) that have occurred inside the confinement (shown in the column named "Temperature range"). The maximum temperature inside the confinement compared to the actual maximum applied heat shows the potential in reduction of heat gain in the event of using a certain panel (referred to in the table as "Peak temperature reduction"). The reduction in peak temperatures is calculated as (the Max temp. of chamber – Max. temp. inside the confinement). The table also shows the variation in temperature fluctuation which was calculated as a percentage based on the difference of temperatures measured inside and outside the confinement ("Max. temp. inside the confinement – Min temp. inside the confinement" / "Max. temp in chamber - Min. Temp. in chamber" * 100 %), thus, showing the potential of using such panels to mitigate heat fluctuations. This also shows the influence of the duration of exposure to heat has on the ability to mitigate fluctuations. The results additionally show the shift in the peak temperature time due to the presence of each panel, which is a property that could be utilised in many applications such as heat storage devices.

Table 3: Thermal measurement of panels under heat profiles.

Heat profile No.	Chamber temp. ranges (°C)	Control panel				1 cm Air gap panel				Wood shavings			
		Temp. range (°C)	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction (°C)	Temp. range (°C)	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction (°C)	Temp. range (°C)	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction (°C)
1	15 - 52.5	15 - 49.8	92.8	60.3	2.7	15 - 48.1	88.2	66.7	4.4	15 - 48.4	89.1	78.8	4.1
2	35 - 53.8	35 - 53.04	96	9.83	0.76	35 - 52.5	93	19.7	1.3	35 - 52.9	95.2	23.3	0.9
3	35 - 52.6	35 - 49.1	80.1	11.5	3.5	40.8 - 48.7	44.9	23.7	3.9	38.7 - 49	58.5	25.8	3.6
4	35 - 52.3	35 - 46.6	67	9.6	5.7	37.2 - 46.5	53.6	15.7	5.8	40.1 - 46.6	37.6	30	5.7
5	35 - 49.6	35 - 42.4	50.7	18.5	7.2	35 - 42.7	52.7	30.7	6.9	35 - 42.2	49.3	39	7.4
6	35 - 46	35 - 39.9	44.5	7	6.1	35 - 39.9	44.5	18	6.1	35 - 39.8	43.6	44.8	6.2

Heat profile No.	Chamber temp. ranges (°C)	PCM				PCM/Ws			
		Temp. range (°C)	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction (°C)	Temp. range (°C)	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction (°C)
1	15 - 52.5	15 - 46.9	85	74.8	5.6	15 - 46.7	84.5	72.2	5.8
2	35 - 53.8	35 - 51.6	88	24.8	2.2	35 - 52.5	93	23.7	1.3
3	35 - 52.6	38.7 - 46.9	46.6	27.1	5.7	39.7 - 48.8	51.7	28.3	3.8
4	35 - 52.3	37.2 - 45.6	48.5	32.5	6.7	40 - 45.7	32.9	34	6.6
5	35 - 49.6	35 - 42.0	47.9	36.1	7.6	38.8 - 42	21.9	41.1	7.6
6	35 - 46	35 - 39.3	39	21.7	6.7	35 - 39.4	40	40.5	6.6

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In heat profile 1, shown in Figure 6(A), there was a reduction in the peak air temperature and a shift in the peak temperature time for all panels. As expected, the control panel has shown the least influence on the temperatures as it only consists of a 2 mm Plexiglass panel. The “1 cm” air gap panel showed more influence as it resulted in decreased temperatures in comparison with the control panel. This is due to the effect of the air gap which acts as thermal insulation to an extent [153–157]. The Ws panel has shown reduction in temperature close to this of the “1 cm” air gap panel. The most thermal influence was observed in both the PCM and the PCM/Ws panel. A negligible difference in temperature reduction was present between both mentioned panels. As for temperature fluctuation, similar results can be observed in all panels. The PCM and the PCM/Ws panel have shown the least fluctuation percentage in comparison with the other panels. This is also true for the peak heat shift durations. It is noted also that heat profile 1 showed the largest heat peak time shift in comparison with other heat profiles. Although the increase of temperatures was almost identical in all panels, the pace at which temperatures dropped inside the confinement is not as identical. The control panel was the fastest to cool down. The “1 cm” air gap panel was slower to cool. The PCM and the PCM/Ws however, were the last to cool. This is possibly due to the latent heat effect of the PCM [158–160].

In heat profile 2, shown in Figure 6(B), similar results as heat profile 1 can be seen. However, it is noted that the peak temperatures of panels were higher than those of heat profile 1. This is possibly due to the applied heat increasing rapidly to 54°C within 1.5 hours of the test then stabilizing for the rest of the duration of the test. This implies that the fluctuation of temperatures may be less reduced if the temperature change is slow as this would allow for the heat to be further conducted through the panels thus causing further increasing and decreasing in the temperature inside the confinement. Similar results are shown in the rest of the heat profiles in regards to the performance of the panels shown in Figure 6(C, D, E & F). It is evident that there is a strong correlation between the duration of the cycle and the performance of the panels. In cycles with longer durations such as in heat profile 3 and 4, the temperatures inside the confinement were found to be fluctuating relatively higher. Whereas in heat profiles with shorter cycles such as heat profile 5 and 6, the fluctuations were found to be lower. It is important to note that this is the case for all the tested panels although the PCM/Ws was seen to have the least fluctuation in all heat profiles regardless of the duration of the cycle. Figure 7(A) shows the relation between cycle duration and the percentage of fluctuation in the tested panels based on the logged measurements of this investigation.

As for the heat peak time shift which represents the duration elapsed from the point that the maximum air temperature occurs inside the chamber and the point that the maximum air temperature is reached inside the confinement, it is evident that there is a minor correlation between the duration of heat application and shift in peak temperature, as seen in Figure 7(B). To elucidate, despite several inconsistencies, the shift seems to increase as the duration of exposure to heat is decreased. An exception to this is profile 1, in which, the largest shifts have been observed despite exerting the most duration of exposure to heat. This may be explained as a result of the highly gradual mode of increase and decrease of heat. The gradual increase in heat allows for the PCM to reach its melting point after a longer duration without being affected by the heat prior to this point. It is worthy to note that the Ws, PCM and PCM/Ws panels have shown the most shift duration, with the PCM and PCM/Ws performing most efficiently in this regard in most of the heat profiles. It is important to point out that the type of PCM will influence its latent heat capacity thus affecting its capability to shift the heat peak [161], other types of PCMs are able to cause an extended heat peak shift as observed in the work of Chung and Park [96], Piselli et al. [97] and Principi and Fioretti [162] discussed earlier. This is true also for the reduction in the peak temperature. All panels

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have resulted in a reduction that ranged from an insignificant reduction (such as 0.76°C in the control panel) to very significant reductions (such as 7.6°C in the PCM panel). It is evident that both the PCM and PCM/WS panel have resulted in the most reduction in all heat profile due to the melting properties of the PCM as discussed earlier in literature. However, it can be seen also that the reduction is at its greatest the shorter the heat cycle is. This can be elucidated as due to the lack of sufficient duration that allows the tested panel to gain heat so as to raise its temperature. Hence, it can be inferred that heat profile 1 and profile 2 represent a more accurate assessment of the temperature reduction capabilities of the tested panels as they have longer cycle durations (24 hours and 12 hours). Whereas, heat profile 3,4,5 and 6 may represent temperature reduction of these panel in conditions were rapid changes in temperature are occurring.

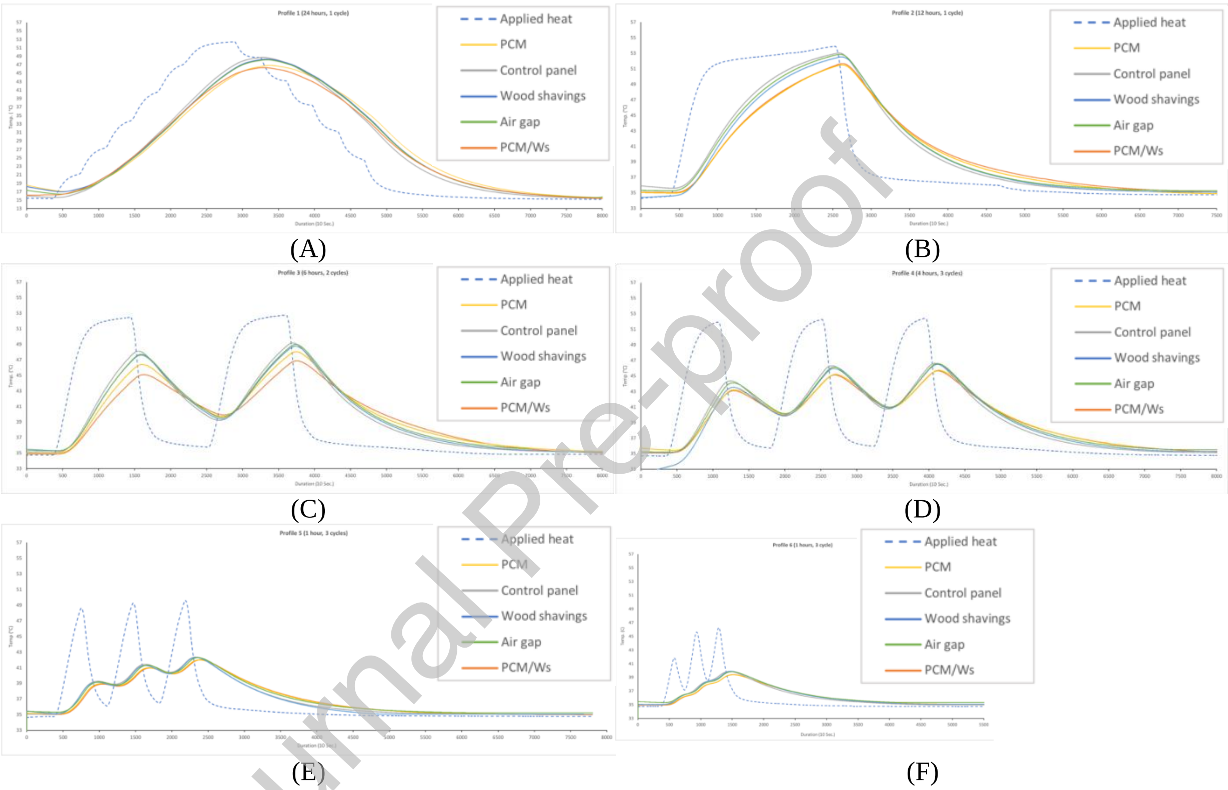

Figure 6: Temperatures of all panels during testing. (A) Profile 1. (B) Profile 2. (C) Profile 3. (D) Profile 4. (E) Profile 5. (F) Profile 6.

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It can be seen that the thermal performance of the PCM and the PCM/Ws amalgam are similar to a large extent. For further comparison, the area encompassed under the curves of the mentioned earlier panels, represented earlier, are compared. Such areas can be indicative of the energy exerted inside the confinement during testing the mentioned panels. Trapezoidal approximation is used to calculate the mentioned areas. Figure 7(C) shows a comparison between the mentioned panels for all heat profiles. It can be seen that the performance of the panels in terms of energy is similar to a large extent. It may be worthy to note that the area under profile 1 curves are clearly much larger, which is consistent with the duration of applied heat for that profile. The areas for Profiles 5 and 6, however, are seen to particularly small a result of the applied heat fluctuating. This is to imply that the effect of heat fluctuation on the applied heat is similar to the effect of reducing the maximum applied temperature in terms of exerted energy. Most importantly, it can be observed from the measurements discussed earlier that although both PCMs and wood shavings have significant thermal performance, the amalgamation of both materials has not resulted in a significant thermal enhancement in the thermal performance of the panels. The measured data shows that the performance of the PCM panel and the PCM/Ws panel is almost identical. Thus, it can be inferred that adding wood shavings to PCMs would not result in enhancing the thermal performance. The values of thermal conductivities of PCM and wood-shaving can explain this fact. Studies show that the thermal conductivity of paraffin waxes, as PCM, of similar melting points to this used in the present study to be around 0.20 to 0.22 W/(m·K) [163–170]. Whereas, the thermal conductivity of MDF/plywood wood-shavings can be as low as 0.11 to 0.17 W/(m·K) [171–177] and in some cases as low as 0.03 W/(m·K) [178,179]. The inherent low thermal conductivity of wood-shavings, compared to this of PCM, can explain the fact that replacing an amount of PCM with a similar volume of wood-shavings will not negatively impact the overall thermal insulation performance. Meaning that, within the amalgam panels, a portion of the denser PCM content is replaced with a material of a lower thermal conductivity, wood-shavings, which increases its overall insulation capabilities and reduces weight due to its relative light weight.

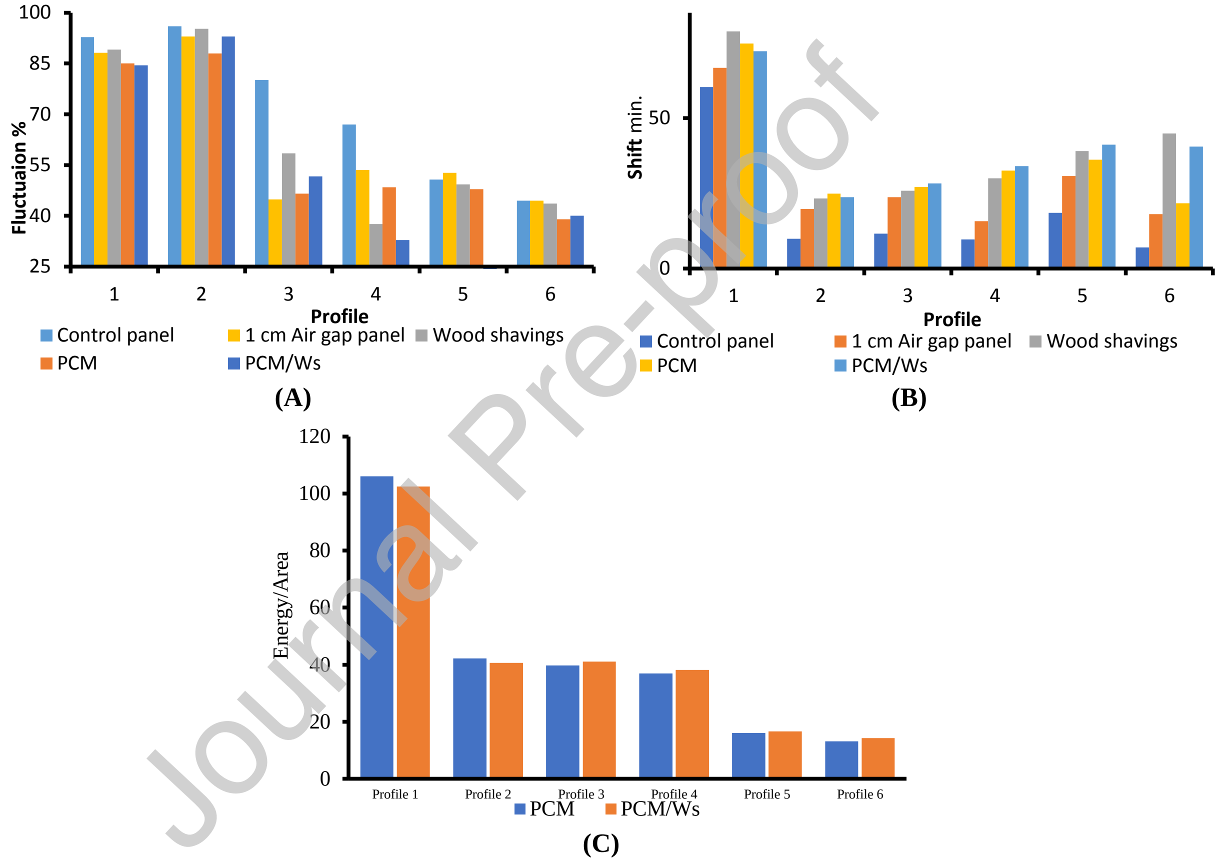

Figure 7: (A) Relation between observed temperature fluctuations in all panels and duration of heat profile cycles. (B) Relation between shift in peak temperatures in all panels and duration of heat profile cycles. (C) Comparison of area under curves for panels.

From a constructional perspective, the amalgamation of these two materials can be of good use. As thermal insulation is applied to the exterior of buildings, this presents a structural load that is taken into consideration during the construction process. Heavier loads would result in more strain on structural elements which require further structural support thus increasing cost. However, having a density of 0.1 g/cm^3, the addition of wood shavings to PCM would result in a significantly lower weight with the same, if not improved, thermal performance. For example, the PCM panel mentioned earlier was filled with 380 g of PCMs (with the density of 9.95 g/cm^3). The thermal performance of the mentioned panel was matched and improved in some cases with the usage of the PCM/Ws which contained 260g of PCMs and 40g of wood shavings with a total weight of 300g. This constitutes for a weight reduction of 80g (20.94 % of total weight). It is important to note that such reduction in weight can be of significant influence in certain area in the world where traditional architecture prevails. In such buildings, considerably thick insulation may be applied to counter extreme wheather conditions, such as rural egyptian architecture built in hot-arid desert climates for instance [180], where insulations can reach a thickness of over 50cm. In fact, many countries around the world still utilise such vernacular building approachs to the present day, such as India [181,182], Yamen [183], Macedonia [184], Myanmar [185], Nepal [186], Spain [187], Romania [188] and Japan [189]. Such buildings carry a large potential to benefit from insulation solutions such as this presented in the present study, where a saving in weight can be highly advantageous.

3. Conclusions

The appraisal of literature presented in this work identified that the use of PCMs, wood shavings and other natural materials as an innovative approach for passive thermal control is highly promising at low cost. However, attempts to combine these materials to gain enhanced thermal performance, although promising, has been performed using complex techniques that may be unsuitable where high-tech is not widely available. Little or no attempts have been carried out to investigate possible gains through simple amalgamation of PCMs and wood shavings. In the context of this article, this was investigated with regards to not only thermal aspect but possible other gains. Comparison of the tested materials shows the following:

- PCMs and PCMs submerged in wood shaving have shown to have better thermal performance compared to wood shavings (in the Ws panel). However, measurements have shown that both PCMs and PCMs/wood shavings have very similar thermal performance, with PCM/wood shavings demonstrating a slightly better performance. This implies that adding amounts of wood shavings to PCMs would not result in any significant enhancement in the thermal performance.
- Although no or little thermal gain can be achieved from submerging wood shavings in PCM, from a construction perspective, advantageous gains may be achieved. Namely, a reduction in weight of 22.94% may be achieved when using mixture of PCMs and wood shavings rather than using PCMs, with almost identical thermal performance. This is also economically advantageous as wood shavings are typically of low cost as a by-product of industrial processes. Hence, replacing amounts of PCM, in PCM related applications, with wood-shavings will certainly reduce thermal insulation costs.
- PCMs and wood shavings submerged in PCMs are able to mitigate heat gain significantly. In cases of long heat cycles, the peak temperature was reduced by up to 5.8°C. In cycles that have shorter durations, the heat peak reduction was up to 7.6°C. It should be noted that this reduction was achieved using 1 cm thick panels. Similar panels with larger thicknesses can have significantly better reduction in temperatures. This highlights the advantageous attribute of weight reduction through using wood-shavings.
- The experimental study shows that PCMs and wood shavings submerged in PCMs have a good potential to reduce air temperature fluctuations. For example, the PCM/Ws panel has shown a notable reduction in air temperature fluctuations (by 15.5% to 60%) compared to the thermal performance of the control panel (reduced fluctuations by 7.2% to 55.5%) and the 1 cm air gap panel (reduced fluctuations by 11.8% to 55.5%). This is true for all of the tested heat profiles which have different

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cycles of high/low temperatures with various cycle durations. The reduction in fluctuations is evidently affected by its duration and intensity.

- A shift in the peak temperature can be achieved using thermal insulation systems, depending on the system's latent heat properties and the durations of the applied heat cycles. However, it is clear that adding wood shavings to PCM in an insulation system will not have a significant effect in the duration of the heat peak shift.

The results of this investigation have shown that, in addition to PCMs having the capability to reduce heat conduction through building walls, they are able to play a good role in mitigating air temperature fluctuations and cause a shift in the heat peak which may in certain cases be beneficial. More importantly, the data has shown that adding wood shaving to PCMs on a thermal insulation system in a simple submerged manner would not negatively affect the performance of this system, and, would result in a reduction of weight and cost. This reduction is of high significance in terms of construction requirements and cost. Other materials have such qualities which is a good area for future research. It is evident that further studies are needed to comprehend possible gains of amalgamating PCMs with natural low-cost substances to further improve thermal, technical and economic aspects of thermal insulation systems.

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CRediT statements

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Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the article entitled " Potential gains from the amalgamation of Phase Changing Materials (PCMs) and wood shavings".

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5. References

[1] Amira Elnokaly and Ahmed Elseragy 2013 Sustainable Heritage Development: Learning from Urban Conservation of Heritage Projects in Non Western Contexts European Journal of Sustainable Development 2

[2] Fathy 1986 Natural Energy and Vernacular Architecture : Hassan Fathy : 9780226239170

[3] Koch-Nielsen H 2013 Stay Cool : A Design Guide for the Built Environment in Hot Climates (Routledge)

[4] Ayoub M and Elseragy A 2018 Parameterization of traditional domed-roofs insolation in hot-arid climates in Aswan, Egypt Energy & Environment 29 109–30

[5] Elnokaly A, Ayoub M and Elseragy A 2019 Parametric investigation of traditional vaulted roofs in hot-arid climates Renewable Energy 138 250–62

[6] Elnokaly A and Elseragy A 2007 What impedes the development of renewable energy technology in Egypt MCEET 2007 Sustainable Energy: Technologies, Materials and Environmental Issues (Cairo, Egypt: MCEET, Cairo, Egypt)

[7] Fahmy M, Mahdy M M and Nikolopoulou M 2014 Prediction of future energy consumption reduction using GRC envelope optimization for residential buildings in Egypt Energy and Buildings 70 186–93

[8] Zeng R, Wang X, Di H, Jiang F and Zhang Y 2011 New concepts and approach for developing energy efficient buildings: Ideal specific heat for building internal thermal mass Energy and Buildings 43 1081–90

[9] Meyn S K 2000 Heat fluxes through roofs and their relevance to estimates of urban heat storage (University of British Columbia)

[10] Ramamurthy P, Sun T, Rule K and Bou-Zeid E 2015 The joint influence of albedo and insulation on roof performance: An observational study Energy and Buildings 93 249–58

[11] Santamouris M, Synnefa A and T Karlessi 2011 Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions - Dimensions

[12] Frontczak M and Wargocki P 2011 Literature survey on how different factors influence human comfort in indoor environments Building and Environment 46 922–37

[13] Qadi S A, Sodagar B and Elnokaly A 2018 Estimating the heating energy consumption of the residential buildings in Hebron, Palestine Journal of Cleaner Production 196 1292–305

[14] Asdrubali F, D'Alessandro F, Baldinelli G and Bianchi F 2014 Evaluating in situ thermal transmittance of green buildings masonries—A case study Case Studies in Construction Materials 1 53–9

[15] Korjenic A, Petránek V, Zach J and Hroudová J 2011 Development and performance evaluation of natural thermal-insulation materials composed of renewable resources Energy and Buildings 43 2518–23

[16] Zach J, Hroudová J, Brožovský J, Krejza Z and Gailius A 2013 Development of Thermal Insulating Materials on Natural Base for Thermal Insulation Systems Procedia Engineering 57 1288–94

[17] Feist W, Schnieders J, Dorer V and Haas A 2005 Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept Energy & Buildings 11 1186–203

[18] Holmes M J and Hacker J N 2007 Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century Energy and Buildings 39 802–14

[19] Elnokaly A and Keeling I 2016 An Empirical Study Investigating the Impact of Micro-algal Technologies and their Application within Intelligent Building Fabrics Procedia - Social and Behavioral Sciences 216 712–23

[20] Elnokaly A 2014 CFD Analysis of Tensile Conical Membrane Structures as Microclimate Modifiers in Hot Arid Regions Civil Engineering and Architecture Hrpub 2 92–102

[21] Burillo D, Chester M V, Pincetl S, Fournier E D and Reyna J 2019 Forecasting peak electricity demand for Los Angeles considering higher air temperatures due to climate change Applied Energy 236 1–9

[22] Jovanović S, Savić S, Bojić M, Djordjević Z and Nikolić D 2015 The impact of the mean daily air temperature change on electricity consumption Energy 88 604–9

[23] Özbalta T G, Sezer A and Yıldız Y 2012 Models for Prediction of Daily Mean Indoor Temperature and Relative Humidity: Education Building in Izmir, Turkey Indoor and Built Environment 21 772–81

[24] Zhang S, Cheng Y, Fang Z, Huan C and Lin Z 2017 Optimization of room air temperature in stratum-ventilated rooms for both thermal comfort and energy saving Applied Energy 204 420–31

[25] Li D, Wu Y, Wang B, Liu C and Arıcı M 2020 Optical and thermal performance of glazing units containing PCM in buildings: A review Construction and Building Materials 233 117327

[26] Singh Rathore P K, Shukla S K and Gupta N K 2020 Potential of microencapsulated PCM for energy savings in buildings: A critical review Sustainable Cities and Society 53 101884

[27] Kant K, Shukla A and Sharma A 2017 Heat transfer studies of building brick containing phase change materials Solar Energy 155 1233–42

[28] Vicente R and Silva T 2014 Brick masonry walls with PCM macrocapsules: An experimental approach Applied Thermal Engineering 67 24–34

[29] Silva T, Vicente R, Soares N and Ferreira V 2012 Experimental testing and numerical modelling of masonry wall solution with PCM incorporation: A passive construction solution Energy and Buildings 49 235–45

[30] da Cunha S R L and de Aguiar J L B 2020 Phase change materials and energy efficiency of buildings: A review of knowledge Journal of Energy Storage 27 101083

[31] Yang L, Huang J and Zhou F 2020 Thermophysical properties and applications of nano-enhanced PCMs: An update review Energy Conversion and Management 214 112876

[32] Álvarez S, Cabeza L F, Ruiz-Pardo A, Castell A and Tenorio J A 2013 Building integration of PCM for natural cooling of buildings Applied Energy 109 514–22

[33] Cao V D, Pilehvar S, Salas-Bringas C, Szczotok A M, Bui T Q, Carmona M, Rodriguez J F and Kjøniksen A-L 2019 Thermal analysis of geopolymer concrete walls containing microencapsulated phase change materials for building applications Solar Energy 178 295–307

[34] de Gracia A 2019 Dynamic building envelope with PCM for cooling purposes – Proof of concept Applied Energy 235 1245–53

[35] Lei J, Yang J and Yang E-H 2016 Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore Applied Energy 162 207–17

[36] Chou H-M, Chen C-R and Nguyen V-L 2013 A new design of metal-sheet cool roof using PCM Energy and Buildings 57 42–50

[37] Ahangari M and Maerefat M 2019 An innovative PCM system for thermal comfort improvement and energy demand reduction in building under different climate conditions Sustainable Cities and Society 44 120–9

[38] Izquierdo-Barrientos M A, Belmonte J F, Rodríguez-Sánchez D, Molina A E and Almendros-Ibáñez J A 2012 A numerical study of external building walls containing phase change materials (PCM) Applied Thermal Engineering 47 73–85

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[39] Xie J, Wang W, Liu J and Pan S 2018 Thermal performance analysis of PCM wallboards for building application based on numerical simulation Solar Energy 162 533–40

[40] Biswas K, Shukla Y, Desjarlais A and Rawal R 2018 Thermal characterization of full-scale PCM products and numerical simulations, including hysteresis, to evaluate energy impacts in an envelope application Applied Thermal Engineering 138 501–12

[41] Wang Q, Wu R, Wu Y and Zhao C Y 2018 Parametric analysis of using PCM walls for heating loads reduction Energy and Buildings 172 328–36

[42] Buonomano A and Guarino F 2020 The impact of thermophysical properties and hysteresis effects on the energy performance simulation of PCM wallboards: Experimental studies, modelling, and validation Renewable and Sustainable Energy Reviews 126 109807

[43] Wang H, Lu W, Wu Z and Zhang G 2020 Parametric analysis of applying PCM wallboards for energy saving in high-rise lightweight buildings in Shanghai Renewable Energy 145 52–64

[44] Li C, Yu H, Song Y, Tang Y, Chen P, Hu H, Wang M and Liu Z 2020 Experimental thermal performance of wallboard with hybrid microencapsulated phase change materials for building application Journal of Building Engineering 28 101051

[45] Wi S, Chang S J and Kim S 2020 Improvement of thermal inertia effect in buildings using shape stabilized PCM wallboard based on the enthalpy-temperature function Sustainable Cities and Society 56 102067

[46] Yeon J H 2020 Thermal behavior of cement mortar embedded with low-phase transition temperature PCM Construction and Building Materials 252 119168

[47] Costa J A C, Martinelli A E, do Nascimento R M and Mendes A M 2020 Microstructural design and thermal characterization of composite diatomite-vermiculite paraffin-based form-stable PCM for cementitious mortars Construction and Building Materials 232 117167

[48] Frigione M, Lettieri M, Sarcinella A and Barroso de Aguiar J 2020 Sustainable polymer-based Phase Change Materials for energy efficiency in buildings and their application in aerial lime mortars Construction and Building Materials 231 117149

[49] Li L, Yu H and Liu R 2017 Research on composite-phase change materials (PCMs)-bricks in the west wall of room-scale cubicle: Mid-season and summer day cases Building and Environment 123 494–503

[50] Olivieri L, Tenorio J A, Revuelta D, Navarro L and Cabeza L F 2018 Developing a PCM-enhanced mortar for thermally active precast walls Construction and Building Materials 181 638–49

[51] Rao V V, Parameshwaran R and Ram V V 2018 PCM-mortar based construction materials for energy efficient buildings: A review on research trends Energy and Buildings 158 95–122

[52] Saxena R, Rakshit D and Kaushik S C 2020 Experimental assessment of Phase Change Material (PCM) embedded bricks for passive conditioning in buildings Renewable Energy 149 587–99

[53] Gao Y, He F, Meng X, Wang Z, Zhang M, Yu H and Gao W 2020 Thermal behavior analysis of hollow bricks filled with phase-change material (PCM) Journal of Building Engineering 31 101447

[54] Dabiri S, Mehrpooya M and Nezhad E G 2018 Latent and sensible heat analysis of PCM incorporated in a brick for cold and hot climatic conditions, utilizing computational fluid dynamics Energy 159 160–71

[55] Vinayaka Ram V, Singhal R and Parameshwaran R 2020 Energy efficient pumpable cement concrete with nanomaterials embedded PCM for passive cooling application in buildings Materials Today: Proceedings

[56] Cabeza L F, Navarro L, Pisello A L, Olivieri L, Bartolomé C, Sánchez J, Álvarez S and Tenorio J A 2020 Behaviour of a concrete wall containing micro- encapsulated PCM after a decade of its construction Solar Energy 200 108–13

[57] Mohseni E, Tang W, Khayat K H and Cui H 2020 Thermal performance and corrosion resistance of structural-functional concrete made with inorganic PCM Construction and Building Materials 249 118768

[58] Benkaddour A, Faraji M and Faraji H 2020 Numerical study of the thermal energy storage behaviour of a novel composite PCM/Concrete wall integrated solar collector Materials Today: Proceedings

[59] Arivazhagan R, Arun Prakash S, Kumaran P, Sankar S, Loganathan G B and Arivarasan A 2020 Performance analysis of concrete block integrated with PCM for thermal management Materials Today: Proceedings 22 370–4

[60] Erlbeck L, Schreiner P, Schlachter K, Dörnhofer P, Fasel F, Methner F-J and Rädle M 2018 Adjustment of thermal behavior by changing the shape of PCM inclusions in concrete blocks Energy Conversion and Management 158 256–65

[61] Guo R, Pan Y, Cai L and Hino S 2018 Bonding behavior of CFRP grid-concrete with PCM shotcrete Engineering Structures 168 333–45

[62] Berardi U and Gallardo A A 2019 Properties of concretes enhanced with phase change materials for building applications Energy and Buildings 199 402–14

[63] Arivazhagan R, Arun Prakash S, Kumaran P, Sankar S, Loganathan G B and Arivarasan A 2019 Performance analysis of concrete block integrated with PCM for thermal management Materials Today: Proceedings

[64] Essid N, Loulizi A and Neji J 2019 Compressive strength and hygric properties of concretes incorporating microencapsulated phase change material Construction and Building Materials 222 254–62

[65] D'Alessandro A, Pisello A L, Fabiani C, Ubertini F, Cabeza L F and Cotana F 2018 Multifunctional smart concretes with novel phase change materials: Mechanical and thermo-energy investigation Applied Energy 212 1448–61

[66] Cao V D, Pilehvar S, Salas-Bringas C, Szczotok A M, Valentini L, Carmona M, Rodriguez J F and Kjøniksen A-L 2018 Influence of microcapsule size and shell polarity on thermal and mechanical properties of thermoregulating geopolymer concrete for passive building applications Energy Conversion and Management 164 198–209

[67] Wi S, Yang S, Lee J, Chang S J and Kim S 2019 Dynamic heat transfer and thermal performance evaluation of PCM-doped hybrid hollow plaster panels for buildings Journal of Hazardous Materials 374 428–36

[68] Mekaddem N, Ali S B, Fois M and Hannachi A 2019 Paraffin/ Expanded Perlite/Plaster as Thermal Energy Storage Composite Energy Procedia 157 1118–29

[69] Pavlík Z, Fořt J, Pavlíková M, Pokorný J, Trník A and Černý R 2016 Modified lime-cement plasters with enhanced thermal and hygric storage capacity for moderation of interior climate Energy and Buildings 126 113–27

[70] Asimakopoulou E K, Kolaitis D I and Founti M A 2015 Fire safety aspects of PCM-enhanced gypsum plasterboards: An experimental and numerical investigation Fire Safety Journal 72 50–8

[71] Chung O, Jeong S-G, Yu S and Kim S 2014 Thermal performance of organic PCMs/micronized silica composite for latent heat thermal energy storage Energy and Buildings 70 180–5

[72] Feczkó T, Trif L and Horák D 2016 Latent heat storage by silica-coated polymer beads containing organic phase change materials Solar Energy 132 405–14

[73] Jeong S-G, Jeon J, Cha J, Kim J and Kim S 2013 Preparation and evaluation of thermal enhanced silica fume by incorporating organic PCM, for application to concrete Energy and Buildings 62 190–5

[74] Liu L, Zheng K, Yan Y, Cai Z, Lin S and Hu X 2018 Graphene Aerogels Enhanced Phase Change Materials prepared by one-pot method with high thermal conductivity and large latent energy storage Solar Energy Materials and Solar Cells 185 487–93

[75] Serrano S, Barreneche C, Navarro A, Haurie L, Fernandez A I and Cabeza L F 2016 Use of multi-layered PCM gypsums to improve fire response. Physical, thermal and mechanical characterization Energy and Buildings 127 1–9

[76] Yang J, Qi G-Q, Bao R-Y, Yi K, Li M, Peng L, Cai Z, Yang M-B, Wei D and Yang W 2018 Hybridizing graphene aerogel into three-dimensional graphene foam for high-performance composite phase change materials Energy Storage Materials 13 88–95

[77] Zou D, Ma X, Liu X, Zheng P and Hu Y 2018 Thermal performance enhancement of composite phase change materials (PCM) using graphene and carbon nanotubes as additives for the potential application in lithium-ion power battery International Journal of Heat and Mass Transfer 120 33–41

[78] Zhu Y, Qin Y, Liang S, Chen K, Tian C, Wang J, Luo X and Zhang L 2019 Graphene/SiO2/n-octadecane nanoencapsulated phase change material with flower like morphology, high thermal conductivity, and suppressed supercooling Applied Energy 250 98–108

[79] Eanest Jebasingh B and Valan Arasu A 2020 A detailed review on heat transfer rate, supercooling, thermal stability and reliability of nanoparticle dispersed organic phase change material for low-temperature applications Materials Today Energy 16 100408

[80] Eanest Jebasingh B and Valan Arasu A 2020 A comprehensive review on latent heat and thermal conductivity of nanoparticle dispersed phase change material for low-temperature applications Energy Storage Materials 24 52–74

[81] Laraib Tariq S, Muhammad Ali H, Ammar Akram M, Mansoor Janjua M and Ahmadlouydarab M 2020 Nanoparticles enhanced Phase Change Materials (NePCMs)-A Recent Review Applied Thermal Engineering 115305

[82] Wong-Pinto L-S, Milian Y and Ushak S 2020 Progress on use of nanoparticles in salt hydrates as phase change materials Renewable and Sustainable Energy Reviews 122 109727

[83] Sheikholeslami M, Keshteli A N and Babazadeh H 2020 Nanoparticles favorable effects on performance of thermal storage units Journal of Molecular Liquids 300 112329

[84] Huang X, Chen X, Li A, Atinafu D, Gao H, Dong W and Wang G 2019 Shape-stabilized phase change materials based on porous supports for thermal energy storage applications Chemical Engineering Journal 356 641–61

[85] Li M and Mu B 2019 Effect of different dimensional carbon materials on the properties and application of phase change materials: A review Applied Energy 242 695–715

[86] Rathore P K S and Shukla S K 2019 Potential of macroencapsulated PCM for thermal energy storage in buildings: A comprehensive review Construction and Building Materials 225 723–44

[87] Rodríguez-Cumplido F, Pabón-Gelves E and Chejne-Jana F 2019 Recent developments in the synthesis of microencapsulated and nanoencapsulated phase change materials Journal of Energy Storage 24 100821

[88] Santos T, Kolokotroni M, Hopper N and Yearley K 2019 Experimental study on the performance of a new encapsulation panel for PCM's to be used in the PCM-Air heat exchanger Energy Procedia 161 352–9

[89] Yan T, Gao J, Xu X, Xu T, Ling Z and Yu J 2019 Dynamic simplified PCM models for the pipe-encapsulated PCM wall system for self-activated heat removal International Journal of Thermal Sciences 144 27–41

[90] Alawadhi E M 2015 The design, properties, and performance of concrete masonry blocks with phase change materials Eco-Efficient Masonry Bricks and Blocks ed F Pacheco-Torgal, P B Lourenço, J A Labrincha, S Kumar and P Chindaprasirt (Oxford: Woodhead Publishing) pp 231–48

[91] Yan T, Sun Z, Gao J, Xu X, Yu J and Gang W 2020 Simulation study of a pipe-encapsulated PCM wall system with self-activated heat removal by nocturnal sky radiation Renewable Energy 146 1451–64

[92] Yan W-M, Ho C J, Tseng Y-T, Qin C and Rashidi S 2020 Numerical study on convective heat transfer of nanofluid in a minichannel heat sink with micro-encapsulated PCM-cooled ceiling International Journal of Heat and Mass Transfer 153 119589

[93] Hichem N, Noureddine S, Nadia S and Djamila D 2013 Experimental and Numerical Study of a Usual Brick Filled with PCM to Improve the Thermal Inertia of Buildings Energy Procedia 36 766–75

[94] Rathore P K S and Shukla S K 2020 An experimental evaluation of thermal behavior of the building envelope using macroencapsulated PCM for energy savings Renewable Energy 149 1300–13

[95] Hirmiz R, Teamah H M, Lightstone M F and Cotton J S 2020 Analytical and numerical sizing of phase change material thickness for rectangular encapsulations in hybrid thermal storage tanks for residential heat pump systems Applied Thermal Engineering 170 114978

[96] Chung M and Park J 2017 An Experimental Study on the Thermal Performance of Phase-Change Material and Wood-Plastic Composites for Building Roofs Energies 10 195

[97] Piselli C, Castaldo V L and Pisello A L 2018 How to enhance thermal energy storage effect of PCM in roofs with varying solar reflectance: Experimental and numerical assessment of a new roof system for passive cooling in different climate conditions Solar Energy

[98] Alqallaf H J and Alawadhi E M 2013 Concrete roof with cylindrical holes containing PCM to reduce the heat gain Energy & Buildings Complete 73–80

[99] Asdrubali F, D'Alessandro F and Schiavoni S 2015 A review of unconventional sustainable building insulation materials Sustainable Materials and Technologies 4 1–17

[100] Schiavoni S, D′Alessandro F, Bianchi F and Asdrubali F 2016 Insulation materials for the building sector: A review and comparative analysis Renewable and Sustainable Energy Reviews 62 988–1011

[101] Sheweka S and Elnokaly A 2016 Waste management and material recycle as a potential of sustainable building envelope for low income housing Sustainability and Innovation for the Future 41st IAHS World Congress (Albufeira, Algarve, Portugal)

[102] Pásztory Z, Ronyecz Mohácsiné I and Börcsök Z 2017 Investigation of thermal insulation panels made of black locust tree bark Construction and Building Materials 147 733–5

[103] Abu-Jdayil B, Mourad A-H, Hittini W, Hassan M and Hameedi S 2019 Traditional, state-of-the-art and renewable thermal building insulation materials: An overview Construction and Building Materials 214 709–35

[104] Cetiner I and Shea A D 2018 Wood waste as an alternative thermal insulation for buildings Energy and Buildings 168 374–84

[105] Jerman M, Palomar I, Kočí V and Černý R 2019 Thermal and hygric properties of biomaterials suitable for interior thermal insulation systems in historical and traditional buildings Building and Environment 154 81–8

[106] Lacoste C, El Hage R, Bergeret A, Corn S and Lacroix P 2018 Sodium alginate adhesives as binders in wood fibers/textile waste fibers biocomposites for building insulation Carbohydrate Polymers 184 1–8

[107] Binici H and Aksogan O 2016 Eco-friendly insulation material production with waste olive seeds, ground PVC and wood chips Journal of Building Engineering 5 260–6

[108] Kymäläinen H-R and Sjöberg A-M 2008 Flax and hemp fibres as raw materials for thermal insulations Building and Environment 43 1261–9

[109] Khedari J, Charoenvai S and Hirunlabh J 2003 New insulating particleboards from durian peel and coconut coir Building and Environment 38 435–41

[110] Binici H, Eken M, Dolaz M, Aksogan O and Kara M 2014 An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres Construction and Building Materials 51 24–33

Journal Pre-proof

[111] Benkreira H, Khan A and Horoshenkov K V 2011 Sustainable acoustic and thermal insulation materials from elastomeric waste residues Chemical Engineering Science 66 4157–71
[112] Chikhi M, Agoudjil B, Boudenne A and Gherabli A 2013 Experimental investigation of new biocomposite with low cost for thermal insulation Energy and Buildings 66 267–73
[113] Akaranta O 2000 Production of particle boards from bioresources Bioresource Technology 75 87–9
[114] Akinyemi A B, Afolayan J O and Ogunji Oluwatobi E 2016 Some properties of composite corn cob and sawdust particle boards Construction and Building Materials 127 436–41
[115] Nasir M, Khali D P, Jawaid M, Tahir P M, Siakeng R, Asim M and Khan T A 2019 Recent development in binderless fiber-board fabrication from agricultural residues: A review Construction and Building Materials 211 502–16
[116] Pedieu R, Riedl B and Pichette A 2008 Physical and mechanical properties of panel based on outer bark particles of white birch: Mixed panels with wood particles versus wood fibres Maderas. Ciencia y tecnología 12
[117] Sam-Brew S and Smith G D 2015 Flax and Hemp fiber-reinforced particleboard Industrial Crops and Products 77 940–8
[118] Ghofrani M, Ashori A and Mehrabi R 2017 Mechanical and acoustical properties of particleboards made with date palm branches and vermiculite Polymer Testing 60 153–9
[119] Taha I, Elkafafy M S and El Mously H 2018 Potential of utilizing tomato stalk as raw material for particleboards Ain Shams Engineering Journal 9 1457–64
[120] Klímek P, Meinlschmidt P, Wimmer R, Plinke B and Schirp A 2016 Using sunflower (Helianthus annuus L.), topinambour (Helianthus tuberosus L.) and cup-plant (Silphium perfoliatum L.) stalks as alternative raw materials for particleboards Industrial Crops and Products 92 157–64
[121] Viel M, Collet F and Lanos C 2019 Development and characterization of thermal insulation materials from renewable resources Construction and Building Materials 214 685–97
[122] Wei K, Lv C, Chen M, Zhou X, Dai Z and Shen D 2015 Development and performance evaluation of a new thermal insulation material from rice straw using high frequency hot-pressing Energy and Buildings 87 116–22
[123] Gallegos-Ortega R, Magaña-Guzmán T, Reyes-López J A and Romero-Hernández M S 2017 Thermal behavior of a straw bale building from data obtained in situ. A case in Northwestern México Building and Environment 124 336–41
[124] Pruteanu M 2010 Investigations Regarding the Thermal Conductivity of Straw Bulletin of the Polytechnic Institute of Iasi. Construction and Architecture Section. 8
[125] Rojas C, Cea M, Iriarte A, Valdés G, Navia R and Cárdenas-R J P 2019 Thermal insulation materials based on agricultural residual wheat straw and corn husk biomass, for application in sustainable buildings Sustainable Materials and Technologies 20 e00102
[126] Keskin H, Kucuktuvek M and Guru M 2015 The potential of poppy (Papaver somniferum Linnaeus) husk for manufacturing wood-based particleboards Construction and Building Materials 95 224–31
[127] Sabapathy K A and Gedupudi S 2019 Straw bale based constructions: Measurement of effective thermal transport properties Construction and Building Materials 198 182–94
[128] Brouard Y, Belayachi N, Hoxha D, Ranganathan N and Méo S 2018 Mechanical and hygrothermal behavior of clay – Sunflower (Helianthus annuus) and rape straw (Brassica napus) plaster bio-composites for building insulation Construction and Building Materials 161 196–207
[129] Park J H, Kang Y, Lee J, Chang S J, Wi S and Kim S 2019 Development of wood-lime boards as building materials improving thermal and moisture performance based on hygrothermal behavior evaluation Construction and Building Materials 204 576–85
[130] Park S H and Lee P J 2017 Effects of floor impact noise on psychophysiological responses Building and Environment 116 173–81
[131] Chang S J, Wi S, Lee J and Kim S 2019 Development of vacuum impregnation equipment and preparation of mass/uniform shape-stabilized phase change materials International Journal of Heat and Mass Transfer 132 817–24
[132] Lee J, Wi S, Yun B Y, Chang S J and Kim S 2019 Thermal and characteristic analysis of shape-stabilization phase change materials by advanced vacuum impregnation method using carbon-based materials Journal of Industrial and Engineering Chemistry 70 281–9
[133] Lee J, Wi S, Jeong S-G, Chang S J and Kim S 2017 Development of thermal enhanced n-octadecane/porous nano carbon-based materials using 3-step filtered vacuum impregnation method Thermochimica Acta 655 194–201
[134] Liang B, Lu X, Li R, Tu W, Yang Z and Yuan T 2019 Solvent-free preparation of bio-based polyethylene glycol/wood flour composites as novel shape-stabilized phase change materials for solar thermal energy storage Solar Energy Materials and Solar Cells 200 110037
[135] Liang J, Zhimeng L, Ye Y, Yanjun W, Jingxin L and Changlin Z 2018 Fabrication and characterization of fatty acid/wood-flour composites as novel form-stable phase change materials for thermal energy storage Energy and Buildings 171 88–99
[136] Liu Z, Yu Z (Jerry), Yang T, Qin D, Li S, Zhang G, Haghighat F and Joybari M M 2018 A review on macro-encapsulated phase change material for building envelope applications Building and Environment 144 281–94
[137] Yang H, Wang Y, Yu Q, Cao G, Yang R, Ke J, Di X, Liu F, Zhang W and Wang C 2018 Composite phase change materials with good reversible thermochromic ability in delignified wood substrate for thermal energy storage Applied Energy 212 455–64
[138] Yang H, Wang Y, Yu Q, Cao G, Sun X, Yang R, Zhang Q, Liu F, Di X, Li J, Wang C and Li G 2018 Low-cost, three-dimension, high thermal conductivity, carbonized wood-based composite phase change materials for thermal energy storage Energy 159 929–36
[139] Li Z X, Al-Rashed A, Rostamzadeh M, Kalbasi R, Shahsavar A and Afrand M 2019 Heat transfer reduction in buildings by embedding phase change material in multi-layer walls: Effects of repositioning, thermophysical properties and thickness of PCM Energy Conversion and Management 195 43–56
[140] Ryms M and Klugmann-Radziemska E 2019 Possibilities and benefits of a new method of modifying conventional building materials with phase-change materials (PCMs) Construction and Building Materials 211 1013–24
[141] Zondag H A, de Boer R, Smeding S F and van der Kamp J 2018 Performance analysis of industrial PCM heat storage lab prototype Journal of Energy Storage 18 402–13
[142] Wickramaratne C, Dhau J S, Kamal R, Myers P, Goswami D Y and Stefanakos E 2018 Macro-encapsulation and characterization of chloride based inorganic Phase change materials for high temperature thermal energy storage systems Applied Energy 221 587–96
[143] Roux J-J, Hubert J-L, Virgone J, Rodler A and Kim E-J 2013 Are 3D heat transfer formulations with short time sted and sun patch evolution nececessary for building simulation?
[144] Zebende G F, Brito A A, Silva Filho A M and Castro A P 2018 ρDCCA applied between air temperature and relative humidity: An hour/hour view Physica A: Statistical Mechanics and its Applications 494 17–26
[145] Mba L, Meukam P and Kemajou A 2016 Application of artificial neural network for predicting hourly indoor air temperature and relative humidity in modern building in humid region Energy and Buildings 121 32–42
[146] Melikov A K, Krüger U, Zhou G, Madsen T L and Langkilde G 1997 Air temperature fluctuations in rooms Building and Environment 32 101–14
[147] Soni V, Kumar A and Jain V K 2018 Modeling of PCM melting: Analysis of discrepancy between numerical and experimental results and energy storage performance Energy 150 190–204

[148] Butala V and Stritih U 2009 Experimental investigation of PCM cold storage Energy and Buildings 41 354–9
[149] Majumdar P and Saidbakhsh A 1990 A heat transfer model for phase change thermal energy storage Heat Recovery Systems and CHP 10 457–68
[150] Venkitaraj K P and Suresh S 2017 Experimental study on thermal and chemical stability of pentaerythritol blended with low melting alloy as possible PCM for latent heat storage Experimental Thermal and Fluid Science 88 73–87
[151] Konstantinidis C V 2010 Integration of thermal energy storage in buildings Thesis
[152] Hasnain S M 1998 Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques Energy Conversion and Management 39 1127–38
[153] Arıcı M, Karabay H and Kan M 2015 Flow and heat transfer in double, triple and quadruple pane windows Energy and Buildings 86 394–402
[154] Arıcı M and Kan M 2015 An investigation of flow and conjugate heat transfer in multiple pane windows with respect to gap width, emissivity and gas filling Renewable Energy 75 249–56
[155] Aydin O 2000 Determination of optimum air-layer thickness in double-pane windows Energy and Buildings 32 303–8
[156] Karabay H and Arıcı M 2012 Multiple pane window applications in various climatic regions of Turkey Energy and Buildings 45 67–71
[157] Xamán J, Pérez-Nucamendi C, Arce J, Hinojosa J, Álvarez G and Zavala-Guillén I 2014 Thermal analysis for a double pane window with a solar control film for using in cold and warm climates Energy and Buildings 76 429–39
[158] Du K, Calautit J, Wang Z, Wu Y and Liu H 2018 A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges Applied Energy 220 242–73
[159] Tyagi V V and Buddhi D 2007 PCM thermal storage in buildings: A state of art Renewable and Sustainable Energy Reviews 11 1146–66
[160] Umair M M, Zhang Y, Iqbal K, Zhang S and Tang B 2019 Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storage–A review Applied Energy 235 846–73
[161] Pereira da Cunha J and Eames P 2016 Thermal energy storage for low and medium temperature applications using phase change materials – A review Applied Energy 177 227–38
[162] Principi P and Fioretti R 2012 Thermal analysis of the application of pcm and low emissivity coating in hollow bricks Energy and Buildings 51 131–42
[163] Hussein H, Abed A and Abdulmunem A 2018 An experimental investigation of using aluminum foam matrix integrated with paraffin wax as a thermal storage material in a solar heater
[164] Sadrameli S M, Motaharinejad F, Mohammadpour M and Dorkoosh F 2019 An experimental investigation to the thermal conductivity enhancement of paraffin wax as a phase change material using diamond nanoparticles as a promoting factor Heat Mass Transfer 55 1801–8
[165] Murali G, K.Mayilsamy and T V A 2014 An Experimental Study of PCM-Incorporated Thermosyphon Solar Water Heating System International Journal of Green Energy Volume 12 978–86
[166] Kenisarin M, Mahkamov K, Kahwash F and Makhkamova I 2019 Enhancing thermal conductivity of paraffin wax 53–57 °C using expanded graphite Solar Energy Materials and Solar Cells 200 110026
[167] George M, Pandey A K, Abd Rahim N, Tyagi V V, Shahabuddin S and Saidur R 2020 A novel polyaniline (PANI)/ paraffin wax nano composite phase change material: Superior transition heat storage capacity, thermal conductivity and thermal reliability Solar Energy 204 448–58
[168] Wang N, Zhang X R, Zhu D S and Gao J W 2012 The investigation of thermal conductivity and energy storage properties of graphite/paraffin composites J Therm Anal Calorim 107 949–54
[169] Wang X L, Li B, Qu Z G, Zhang J F and Jin Z G 2020 Effects of graphite microstructure evolution on the anisotropic thermal conductivity of expanded graphite/paraffin phase change materials and their thermal energy storage performance International Journal of Heat and Mass Transfer 155 119853
[170] Buonomo B, Ercole D, Manca O and Nardini S 2017 Numerical investigation on thermal behaviors of two-dimensional latent thermal energy storage with PCM and aluminum foam Journal of Physics: Conference Series 796 012031
[171] Yapici F, Ozcifci A, Esen R and Kurt S 2011 The effect of grain angle and species on thermal conductivity of some selected wood species BioResources 6 2757–62
[172] Yi X, Zhao D, Ou R, Ma J, Chen Y and Wang Q 2017 A Comparative Study of the Performance of Wood-Plastic Composites and Typical Substrates as Heating Floor BioResources 12 2565–78
[173] Li K Y, Fleischmann C M and Spearpoint M J 2013 Determining thermal physical properties of pyrolyzing New Zealand medium density fibreboard (MDF) Chemical Engineering Science 95 211–20
[174] Qi C, Zhang F, Mu J, Zhang Y and Yu Z 2020 Enhanced mechanical and thermal properties of hollow wood composites filled with phase-change material Journal of Cleaner Production 256 120373
[175] Lu X, Liang B, Sheng X, Yuan T and Qu J 2020 Enhanced thermal conductivity of polyurethane/wood powder composite phase change materials via incorporating low loading of graphene oxide nanosheets for solar thermal energy storage Solar Energy Materials and Solar Cells 208 110391
[176] Kočí V, Jerman M, Pavlík Z, Maděra J, Žák J and Černý R 2020 Interior thermal insulation systems based on wood fiberboards: experimental analysis and computational assessment of hygrothermal and energy performance in the Central European climate Energy and Buildings 222 110093
[177] Ikei H, Song C and Miyazaki Y 2017 Physiological Effects of Touching Coated Wood International Journal of Environmental Research and Public Health 14 773
[178] Kotlarewski N J, Ozarska B and Gusamo B K 2014 Thermal Conductivity of Papua New Guinea Balsa Wood Measured using the Needle Probe Procedure BioResources 9 5784–93
[179] Tangjuank S and Kumfu S 2011 Particle Boards from Papyrus Fibers as Thermal Insulation Journal of Applied Sciences Volume 11 (14)
[180] Farouk Mohamed A 2020 Comparative study of traditional and modern building techniques in Siwa Oasis, Egypt: Case study: Affordable residential building using appropriate building technique Case Studies in Construction Materials 12 e00311
[181] Kulshreshtha Y, Mota Nelson J A, Jagadish K S, Bredenoord J, Vardon P J, van Loosdrecht M C M and Jonkers H M 2020 The potential and current status of earthen material for low-cost housing in rural India Construction and Building Materials 247 118615
[182] Chel A, Tiwari G N and Chandra A 2009 A model for estimation of daylight factor for skylight: An experimental validation using pyramid shape skylight over vault roof mud-house in New Delhi (India) Applied Energy 86 2507–19
[183] Attia A S 2020 Traditional multi-story house (Tower House) in Sana'a City, Yemen. An example of sustainable architecture Alexandria Engineering Journal 59 381–7

Journal Pre-proof

[184] Tomovska R and Radivojević A 2017 Tracing sustainable design strategies in the example of the traditional Ohrid house Journal of Cleaner Production 147 10–24
[185] Zune M, Pantua C A J, Rodrigues L and Gillott M 2020 A Review of Traditional Multistage Roofs Design and Performance in Vernacular Buildings in Myanmar Sustainable Cities and Society 102240
[186] Khadka B 2020 Mud masonry houses in Nepal: A detailed study based on entire reconstruction scenario in 31 earthquake-affected districts Structures 25 816–38
[187] Delgado M C J and Guerrero I C 2006 Earth building in Spain Construction and Building Materials 20 679–90
[188] Dutu A, Niste M, Spatarelu I, Dima D I and Kishiki S 2018 Seismic evaluation of Romanian traditional buildings with timber frame and mud masonry infills by in-plane static cyclic tests Engineering Structures 167 655–70
[189] Hassel B I, Kitamori A, Kiho J and Komatsu K 2013 Prefabricated mud wall units based on a traditional Japanese building system: Lateral in-plane performance in terms of connection, and crack development using digital speckle photography International Journal of Sustainable Built Environment 2 1–9

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